学校编码：10384　　　　　　　　　　分类号____密级____
学　　号：23320100154046　　　　　　　　　　UDC____

原模图 LDPC 码的优化设计及性能分析

厦门大学

博　士　学　位　论　文

# 原模图 LDPC 码的优化设计及性能分析

# Design and Performance Analysis of Protograph LDPC Codes

方　毅

指导教师姓名：王　琳　教授
专 业 名 称：通信与信息系统
论文提交日期：2013 年 9 月
论文答辩时间：2013 年 11 月
学位授予日期：2013 年　月

答辩委员会主席：__________
评　　阅　　人：__________

厦门大学

2013 年 11 月

# 厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果，均在文中以适当方式明确标明，并符合法律规范和《厦门大学研究生学术活动规范（试行）》。

另外，该学位论文为（ ）课题（组）的研究成果，获得（ ）课题（组）经费或实验室的资助，在（ ）实验室完成。（请在以上括号内填写课题或课题组负责人或实验室名称，未有此项声明内容的，可以不作特别声明。）

声明人（签名）：

年 月 日

# 厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（　　）1.经厦门大学保密委员会审查核定的保密学位论文，于　　年　　月　　日解密，解密后适用上述授权。

（　　）2.不保密，适用上述授权。

（请在以上相应括号内打"√"或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年　　月　　日

# 摘 要

1963 年，R. Gallager 首次提出了一种性能优秀的纠错码—低密度奇偶校验(Low-Density-Parity-Check, LDPC)码。这种码型在信度传播(Belief Propagation, BP)译码算法下的纠错性能非常接近香农限，并已被广泛应用在各种通信标准之中。然而，传统 LDPC 码存在一些固有的缺陷，如编译码复杂度高、存在错误地板及码率不可扩展等。最近，美国空气动力实验室(Jet Propulsion Laboratory, JPL)提出了一类新型 LDPC 码—原模图 LDPC 码。原模图 LDPC 码克服了传统 LDPC 码的诸多缺点，不仅具有优秀的纠错性能，而且能够实现线性编译码。基于以上优点，美国太空数据系统咨询委员会(Consultative Committee for Space Date Systems)已于 2006 年将该码型推荐给美国国家航空航天局(National Aeronautics and Space Administration)作为深空通信的标准码型。本文利用外信息转移(Extrinsic Information Transfer, EXIT)算法，围绕原模图 LDPC 码在标准和非标准传输环境中的应用进行了系统的研究，主要创新点包括：

(1)在加性高斯白噪声(Additive White Gaussian Noise，AWGN)信道(即标准传输环境)中，对原模图 LDPC 码的编译码算法展开了研究。

1)针对原模图 LDPC 码，本文基于原模图外信息转移(Protograph EXIT, PEXIT)算法和渐近重量分布(Asymptotic Weight Distribution, AWD)函数，提出了一种码型联合优化算法，该算法可在不增加编译码复杂度的前提下，兼顾瀑布区性能，设计出比传统原模图 LDPC 码地板区性能更好的码型。理论分析和仿真结果表明，用该算法设计出的新型原模图 LDPC 码与传统原模图 LDPC 码相比，在高信噪比(Signal-to-Noise-Ratio, SNR)区获得了显著的编码增益，降低了错误地板。

2)对于长 LDPC 码而言，采用信度传播译码算法能够获得靠近香农限的纠错性能。然而，对于中短 LDPC 码，BP 译码算法往往会停止于 LDPC 码的陷阱集(Trapping Set)之中从而无法成功收敛，故 BP 算法只是一种次优的译码算法。为了解决该问题，本文提出了一种联合译码算法—信度传播-麦克斯韦(BP-Maxwell, BM)译码算法。理论分析和仿真结果表明，该译码算法可打破大多数小陷阱集从

而获得比 BP 译码算法更低的误帧率(Frame-Error-Rate, FER)，并缩小与最大似然译码(Maximum Likelihood, ML)之间的性能差距。

(2)在部分响应(Partial Response, PR)信道(即非标准传输环境)中，对原模图 LDPC 码的性能及码型设计进行了研究。

首先，改进了有限长 EXIT 算法，并利用该算法分析了传统原模图 LDPC 码的性能。有限长 EXIT 分析结果表明，由于存在符号间干扰(Intersymbol Interference, ISI)，在 AWGN 信道中性能优秀的传统原模图 LDPC 码不适用于 PR 信道。因此，本文提出了一种新颖的码型设计方案，并且根据该方案构造出了三种新原模图 LDPC 码。EXIT 分析、收敛性能分析及仿真结果表明，这三种新原模图 LDPC 码的纠错性能显著优于传统原模图 LDPC 码，其中两种新原模图 LDPC 码的纠错性能比列重为 3 的规则 LDPC 码(列重为 3 的规则 LDPC 码是 PR 信道中性能最好的 LDPC 码之一)更好。

(3)在衰落信道(即非标准传输环境)中，对原模图 LDPC 码的性能进行了研究。

1) 在瑞利衰落信道中，研究了基于原模图 LDPC 码的单输入多输出(Single-Input-Multiple-Output, SIMO)通信系统的性能。由于传统的 PEXIT 算法不适用于衰落信道，本文根据瑞利衰落的分布特性，提出了一种加权 PEXIT 算法，并用该算法推导了原模图 LDPC 码的译码门限值。理论分析和仿真结果表明，原模图 LDPC 码在高信噪比区的纠错性能优于(3, 6)规则 LDPC 码和最优的非规则 LDPC 码。此外，本文还讨论了分集度对该系统中原模图 LDPC 码的性能影响。因此，原模图 LDPC 码能够成为多天线无线通信系统的备选码型之一。

2)在一类更通用的衰落信道—Nakagami-*m*(简称 Nakagami)衰落信道中，研究了基于原模图 LDPC 码的中继通信系统的性能。首先，扩展了加权 PEXIT 算法，并用于分析原模图 LDPC 码在该信道中的收敛性能。此外，推导了原模图 LDPC 码在译码重传(Decode-and-Forward, DF)和无误重传(Error-Free, EF)两种中继协议下的误比特率(Bit-Error-Rate, BER)理论表达式，并通过仿真验证了它的正确性。与加权 PEXIT 算法相比，该 BER 理论分析方法不仅能够得到更精确的分析结果，而且具有更低的计算复杂度。

(4)在 Nakagami 衰落双向中继信道(即非标准传输环境)中，对基于原模图 LDPC 码的联合信道与物理层网络编码(Joint Channel-and-Physical-Network-Coding, JCNC)通信系统的性能进行了研究。

首先，提出了一种基于 2×2 空时分组码(Space-Time Block Coding, STBC)架构的 JCNC 系统，即 STBC-JCNC 系统。针对该系统，设计了相应预编码方案，提高了中继端解码的效率。其次，在中继译码器中提出了一种简化的似然信息(Log-Likelihood-Ratio, LLR)更新规则。利用该似然信息更新规则和高斯估计(Gaussian Approximation, GA)方法，本文从理论上分析了 STBC-JCNC 系统的 BER 性能，其结果与仿真结果基本一致。该分析方法为无线通信系统中 JCNC 方案的优化设计提供了理论基础。

关键词：信道编码；原模图低密度奇偶校验码；物理层网络编码；外信息转移函数；译码门限值；空时分组码

# Abstract

As a superior error-correction code, low-density-parity-check (LDPC) code was first proposed by R. Gallager in 1963. Exploiting the belief propagation (BP) decoding algorithm, LDPC codes can perform very close to the Shannon limit and hence have been widely used in many communication standards. However, the conventional LDPC codes possess some drawbacks, e.g., relatively high encoding/decoding complexity, error-floor behavior, unextended code rate, etc. Recently, a novel class of LDPC codes, called protogrpah LDPC codes, has been proposed by Jet Propulsion Laboratory (JPL). Protograph LDPC codes overcome most drawbacks of the conventional LDPC codes, i.e., they not only achieve excellent error performance but also possess simple structure to realize linear encoding and decoding. Based on the aforementioned advantages, the consultative committee for space date systems (CCSDS) of United States (US) has recommended the protograph LDPC code to the national aeronautics and space administration (NASA) as the standard error-correction code for space communications. In this dissertation, utilizing the extrinsic information transfer (EXIT) algorithm, we conduct insightful study on the protograph LDPC codes in the standard and non-standard transmission environments. The main contributions of the dissertation lie in:

(1) The encoding and decoding algorithms of the protograph LDPC codes are investigated over additive white Gaussian noise (AWGN) channels (i.e., standard transmission environments).

1) Based on the protograph EXIT (PEXIT) algorithm and the asymptotic weight distribution (AWD) function, we propose a joint optimization algorithm for the protograph LDPC codes. This algorithm can be used to design excellent protograph LDPC codes, which can lower the error floors of the conventional protograph LDPC codes without increasing the encoding/decoding complexity and deteriorating the performance in the waterfall region. The theoretical analyses and simulated results illustrate that the designed protograph LDPC codes have remarkable coding gains as compared to the conventional protograph LDPC codes in the high signal-to-noise-ratio (SNR) region and hence have lower error floors.

2) For long-block length LDPC codes, one can obtain the capacity-approaching performance by using the BP decoding algorithm. Yet, the BP algorithm is found to be stuck in the trapping sets and can not converge successfully when the block lengh is moderate or short. Thus, it is a sub-optimized decoding algorithm in this case. To resolve the above-mentioned problem, we proposed a joint decoding algorithm, namely BP-Maxwell (BM) decoding algorithm. Theoretical analyses and simulated results show that the BM decoding algorithm can break most small trapping sets so as to accomplish lower frame error rate (FER). Moreover, the proposed decoding algorithm reduces the gap to the ML decoder in terms of performance.

(2) The performance of the protograph LDPC codes is invesigated over partial response (PR) channels (i.e., non-standard transmission environments).

We firstly modify the finite-length EXIT algorithm so as to analyze the performance of the protograph LDPC codes. Due to the intersymbol interference (ISI) caused by the PR channels, we observe that the conventional protograph LDPC codes, which have been shown to possess outstanding error performance over AWGN channels, do not perform well through the finite-length EXIT analysis. Consequently, we propose a new design scheme and construct three new types of protograph LDPC codes. The EXIT-chart analysis, the convergence analysis and the simulated results show that all three new codes remarkably outperform the conventional protograph LDPC codes. Moreover, two of the proposed codes are superior to the regular column-weight-3 LDPC code which possesses excellent performance over PR channels.

(3) The performance of the protograph LDPC codes is investigated over fading channels (i.e., non-standard transmission environments).

1) We investigate the performance of the protograph LDPC coded single-input-multiple-output (SIMO) systems over Rayleigh fading channels. As the conventional PEXIT algorithm is not applicable to this type of channel, we propose a weighted PEXIT algorithm and use it for deriving the decoding threshold of the protograph LDPC codes. Theoretical analyses and the simulated results show that the protograph LDPC codes outperform the regular $(3,6)$ LDPC code and the optimized irregular LDPC codes in the high SNR region. Furthermore, we discuss the effect of the diversity order on the performance of protograph LDPC codes in such systems.

Accordingly, the protograph LDPC code stands out as a good candidate for wireless communication systems with multiple antennas.

2) We investigate the performance of the protograph LDPC coded relay systems over Nakagami-*m* (Nakagami in the following) fading channels. The Nakagami fading channel is a general type of fading channels. We firstly extend the weighted PEXIT algorithm in order to analyze the convergence performance of protograph LDPC codes over such channels. Furthermore, we derive the bit-error-rate (BER) expressions for the error-free (EF) relaying protocol and decode-and-forward (DF) relaying protocol. We finally simulate the BER performace of the protograph LDPC codes to verify the accuracy of the analytical results. As a result, the BER theoretical analysis can evaluate the error performance more accurately with lower computational complexity in comparison with the weighted PEXIT algorithm.

(4) The performance of protograph LDPC coded joint channel-and-physical-network-coding (JCNC) systems is investigated over Nakagami-fading two-way relay channels (i.e., non-standard transmission environments).

We firstly propose a 2×2 Alamouti STBC-JCNC system. In such a system, we then design the precoders at two sources so as to implement the iterative decoder more efficiently at the relay. Moreover, we address a simplified updating rule of the log-likelihood-ratio (LLR) in such a decoder. Based on the simplified LLR-updating rule and the Gaussian approximation (GA), we analyze the theoretical BER of the system, which is shown to be reasonably consistent with simulated results. Therefore, the analytical method can facilitate the design of the JCNC for wireless communication scenarios.

**Keywords:** Channel Coding; Protograph Low-Density-Parity-Check (LDPC) Codes; Physical Network Coding (PNC); Extrinsic Information Transfer (EXIT) Function; Decoding Threshold; Space-Time Block Coding (STBC)

# 目 录

# CONTENTS

# 缩略词表

| | | |
|---|---|---|
| ARQ | Automatic Repeat Request | 自动反馈重传 |
| AWD | Asymptotic Weight Distribution | 渐近重量分布 |
| AWGN | Additive White Gaussian Noise | 加性高斯白噪声 |
| BC | Broadcast | 广播 |
| BEC | Binary Erasure Channel | 二进制擦除信道 |
| BER | Bit-Error-Rate | 误比特率 |
| BM | BP-Maxwell | 信度传播-麦克斯韦 |
| BP | Belief Propagation | 信度传播 |
| CSI | Channel State Information | 信道状态信息 |
| DE | Density Evolution/Differential Evolution | 密度进化/差分进化 |
| DF | Decode-and-Forward | 译码重传 |
| EF | Error-Free | 无误重传 |
| EGC | Equal-Gain-Combining | 等增益合并 |
| EPR4 | Extended Class-4 Partial Response | 扩展的第 4 类 PR |
| EXIT | Extrinsic Information Transfer | 外信息转移 |
| FER | Frame-Error-Rate | 误帧率 |
| GA | Gaussian Approximation | 高斯估计 |
| ISI | Intersymbol Interference | 符号间干扰 |
| JCNC | Joint Channel-and-PNC | 联合信道与物理层网络编码 |